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Synovial Tissue Research: State of the Art Review

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Abstract

The synovium is the major target tissue of inflammatory arthritides such as rheumatoid arthritis (RA). The study of synovial tissue has advanced significantly over a number of decades from arthroplasty, blind needle biopsy and more recently facilitated by arthroscopic and ultrasonographic technology that allows easier visualisation and improves the reliability of obtaining synovial biopsies. The potential for study of pathogenesis, patient stratification, discovery of biomarkers and novel targets, as well as validation of therapy, have all been progressed rapidly in the last decade, facilitated by increasingly diverse and sophisticated analytical and technological approaches. In this review we describe clinical and translational developments in the field of synovial tissue research, outlining current and novel investigative technologies, and highlight their application to advance our understanding of the aforegoing imperatives.

Introduction

1.1 General Considerations

Chronic inflammatory arthritides (IA) comprise a heterogeneous group of diseases characterised by inflammation of the synovium, often accompanied by destruction of adjacent cartilage and bone. Inflammation is characterised by synovial neovascularisation, stromal proliferation and leukocyte extravasation.[1] For the purpose of this review we will focus on rheumatoid arthritis (RA), due to its prevalence, and there being the most extensive body of research on this common cause of synovitis. RA is usually persistent and progressive, leading to joint damage, disability and deformity if left untreated. RA is associated with a reduction in quality of life as well as decreased longevity and constitutes an important burden on healthcare spending.[2–4]

Recent years have seen several dramatic advances in the treatment of IA in general, and particularly in RA. The patterns of clinical response are remarkably similar for agents with different targets challenging our understanding of disease mechanisms. While it is true that the last two decades have witnessed an unprecedented, if qualified, success in treating RA, a substantial portion of patients still do not achieve low disease activity or remission.[5,6]

The main challenges in biomedicine and translational research in RA focus on early diagnosis, personalised medicine, and the development of meaningful outcome assessments.[7] It is logical to hypothesise that each of these aims can be facilitated by the identification and development of appropriate biomarkers. However, while peripheral blood biomarkers such as rheumatoid factor and anti-citrullinated peptide antibodies (ACPA) have been shown to be relatively specific and may predict development of RA in asymptomatic individuals,[8,9] they may only be found in 70-80% of RA subjects. Indeed, beyond these factors our repertoire of blood biomarkers to assist with diagnosis, disease progression and response to therapy is currently extremely limited.[10,11]

Since the synovium is the principal target of inflammation in RA, and the specific resident fiblroblast-like synoviocyte (FLS) is implicated in the pathogenesis of synovitis, one promising approach in the search for biomarkers may be the detailed analysis of the inflamed synovial tissue. Using a combination of established methodologies, together with incorporating new high-throughput technologies with the capability of detailed examination of genes and their products on a scale never before possible, a new opportunity awaits in the search for these biomarkers.

1.2 Anatomy and Physiological Regulation of the Synovial Joint

The synovial joint comprises opposing bones, with the articular surface covered by cartilage. The main protein in bone is type I collagen, while cartilage, which is found on the articulating surfaces, comprises mainly type II collagen and proteoglycan molecules. The non-articulating surfaces are lined by a thin adventitious layer known as synovium. Normal synovial tissue comprises 1 to 3 layers of specialized columnar FLS interspersed with macrophages.[12] The entire structure is housed by a fibrous capsule, and together with ligaments, muscles and tendons, this confers strength and stability to the joint.

Several factors contribute to the maintenance of normal homeostasis in the synovial joint. These include normal expression of the protective lubricin[13], FLS secretion of matrix metalloproteinases (MMPs), immune sentinel roles played by resident macrophages and FLS, the regulated entry and exit of leukocytes involved in immune surveillance, and local regulation by cytokines and growth factors.

Cytokines and growth factors are important regulators of FLS and chondrocytes.[14–16] Cytokines are categorized either as pro- or anti-inflammatory depending on their immediate effect on specific tissue, although there is considerable potential for pleiotropism depending on the cells targeted and the microenvironment. These regulators are ubiquitous in the synovium and synovial space and make their way either by filtration from plasma, or secretion by FLS, chondrocytes and the surrounding tissues.[16]

The joint is a dynamic environment that is subject to minor trauma continually, through movement, and in some joints, compression due to weight bearing, and is therefore subject to continued wound healing and repair processes. It is therefore necessary for articular cartilage and adjacent bone to be continually remodelled in a cycle of synthesis and degradation. This requires a balance of anabolic and catabolic enzyme activity in both cartilage and bone.

Carefully regulated proteolytic enzymes are responsible for the balance between anabolic and catabolic processes within the joint and cartilage.[17] Matrix degrading enzymes such as MMPs are present in normal synovial fluid, but are higher in concentration in RA, psoriatic arthritis (PsA) and osteoarthritis (OA).[17–19] The collagenases (MMP-1,-3, -8,-13 and -18) are the most important of these enzymes as they are the only known enzymes that can directly cleave collagen at neutral pH,[20] but other MMPs continue this breakdown when the triple helix collagen structure has become unravelled.[21]

Serine and cysteine proteinases are required to activate pro-MMPs (to MMPs) after they are secreted. Furthermore, inhibitors of these proteinases (e.g. tissue inhibitors of metalloproteinases (TIMPs), and inhibitors of serine proteinases (SERPINs)) are also present

in the normal joint. The levels and activity of these enzymes can be monitored indirectly by measuring their degradation products in the synovial fluid.[22]

1.3 The Inflamed Joint

The inflamed synovium has been studied at several levels: macroscopic, microscopic and molecular. Synovium is the primary target of disturbed immunomodulatory pathways in RA. Rheumatoid synovial tissue appears macroscopically hyperplastic and hypervascular (Figure 1A-B), while microscopically there is intimal lining layer hyperplasia and accumulation of inflammatory cells including T and B lymphocytes, plasma cells, macrophages, neutrophils, mast cells, natural killer and dendritic cells in the synovial sublining (Figure 1C-D).[23] Like the target organ in other autoimmune diseases (e.g. Sjogren's syndrome, autoimmune thyroiditis) infiltrating T and B cells have been demonstrated to form aggregates with varying degrees of organisation, and the potential to produce disease specific ACPA.[24,25]

Angiogenesis accompanies this cell accumulation, but it occurs in an abnormal manner resulting in different patterns of blood vessels associated with particular types of inflammatory arthropathies.[26] Additionally, the new blood vessels appear to be in an immature state.[27] The new vessels allow for increased leucocyte migration and the synovial tissue transforms into an invading 'pannus', that may cause cartilage and bone destruction.[28,29] Despite increased vascular supply, profound hypoxia in inflamed synovial membrane *in vivo* has been demonstrated.[30]

Many of the pathological changes manifest in the inflamed synovial tissue are observable in the synovial fluid (SF), which has also been studied intensively. Inflammation alters the permeability of synovial tissue.[31] In relation to RA synovium, the permeability to large molecules is increased, but that of small molecules is decreased (e.g urea and glucose). This is due to a combination of increased permeability of the vessels, cellular infiltration and synovial hyperplasia. The total protein content in SF is higher in inflammation and synovial inflammation inhibits the ability of the synovium to selectively filter proteins from entering and leaving the joint space.

The molecular weight distribution of the lubrication macromolecule hyaluronic acid (HA) is also altered, with a shift towards lower molecular weight forms in RA.[32] There is increased loss of HA from the joint and the mean HA concentration is lower in OA and RA synovial fluid.[33,34]

Pathological SF samples have markedly raised cytokine concentrations.[35] The role of cytokines in initiating and perpetuating the synovial inflammatory response continues to be studied intensively and has already lead to the development of several useful therapeutic agents, and the identification of further potential targets.[16] Changes in the cellular infiltrate of RA synovial tissue were recognised from an early stage to be associated with the clinical

course of disease and were used to identify specific responses to conventional and biologic disease modifying anti-rheumatic therapy.[36–38]

Synovial biopsy

2.2 Retrieving Synovial Tissue Samples

The utility of synovial biopsy has been demonstrated in increasing our understanding of the pathogenesis of RA, in identifying potential therapeutic targets and evaluating current and new treatments.[36–58]It has also been proposed that synovial biopsies may give insight into the mechanism of action of a given agent.[59]

Synovial tissue may be obtained by needle biopsy, arthroplasty surgery, arthroscopically, or using ultrasound to guide the biopsy needle or grasping forceps (Figure 2).[59] Arthroscopic biopsy allows direct visualisation of the synovium and the operator can select an area of synovium to biopsy. Ultrasound depicts synovial thickness in greyscale and synovial vascularity with Doppler to assist in selecting a suitable biopsy site. While blind biopsy has been validated, arthroscopic and ultrasound guided biopsy are favoured by the majority of investigators for proof of concept experiments, as sampling is more specific for synovial tissue rather than connective tissue.[53]

Arthroscopic and ultrasound guided biopsy are safe and well tolerated. Data from 15,682 arthroscopies performed by rheumatologists revealed a complication rate for haemarthrosis of 0.9%, for deep vein thrombosis of 0.2%, and wound and joint infection both of 0.1%.[60] This incidence is reproducible at other centres where the overall complication rate was shown to be less than 0.3%.Similarly, an overall major complication rate is reported as 0.4% for ultrasound guided biopsy procedures.[61]

One study of biopsies in RA patients taken from both an inflamed knee joint and a small joint, showed similar mean cell numbers for all markers investigated in the synovial sublining in both sample sources.[62] Of further note, patients with clinically evident disease manifest at small joints have been shown to have similar abnormalities in clinically uninvolved knee joints, albeit at lower expression levels.[62-64] However, intimal lining layer hyperplasia appeared to depend on local processes ; there was no correlation of the numbers of intimal macrophages or FLS between the different joints. Consistent with these findings, there are differences in DNA methylation and transcriptome signatures in FLS from different joints of RA patients as well as differences in FLS invasiveness depending on their positional memory. [65, 66] Questions remain about where to biopsy within a given joint. In particular there have been concerns that mediators of inflammation may be differentially expressed in different parts of the same joint, especially between the cartilage pannus junction (CPJ) and non-CPJ sites which are known to behave differently. However for T-cells[67,68], plasma cells[68], several MMPs[68] and granzymes[68], there have been similar results for biopsies from CPJ and non-CPJ sources. One study did find a difference for

macrophages[63], but others did not.[67,68] Studies examining the number of synovial tissue specimens for reproducible research studies suggest at least six biopsy specimens is the optimal number.[59, 70]

Although synovial tissue analysis plays a minor clinical role in the differential diagnosis of arthritis (e.g. infectious, granulomatous, infiltrative diseases or crystal arthropathies), there are still profound unmet needs regarding predictors for diagnosis, disease progression and response to treatment. Therefore, studies of synovium have recently expanded beyond immunohistochemistry to involve methods of tissue digestion, homogenisation and indeed, whole tissue culture. The methods of examining synovial tissue at a molecular level include detailed 'omic' technology discussed in greater detail below. To this end the synovial tissue obtained from the joint is placed on saline-dampened gauze, snap-frozen in OCT or placed directly into RNAlater. The synovial fluid is centrifuged and a cell pellet may be isolated or separated, using Ficoll gradient, will provide synovial fluid mononuclear cells.Synovial fluid may reflect the synovial compartment better than blood but still provides only indirect information therefore studies of the synovium, the target tissue of RA is essential.[71]

Various prognostic biomarkers for RA have been identified in SF and validated in serum.[72] Studies performed using this strategy first identified proteins that may be of interest in the synovial fluid, and then searched for antibodies to these proteins in the plasma.[73]It is possible that this methodology may be useful in future experiments of synovial tissue, and the results of such research may be more easily translated into clinical practice.

Since 2002, cohorts of patients with early arthritis have been gathered. Having a cohort of early arthritis patients with clinical data, histological data, DNA and mRNA arrays plus proteomics is an instrumental resource for investigating differences in synovial tissue, comparing several inflammatory joint diseases with persistent self-limiting, persistent active disease as well as erosive and non-erosive disease.[74]

Most research with synovial biopsies has been performed from RA patients but some results suggest that synovial tissue sampling may be used in other inflammatory arthropathies such as psoriatic arthritis.[71, 75-77] This research aims to gain a fuller understanding of disease pathogenesis, mechanisms of action of current treatments, and the identification of novel targets and biomarkers. Indeed, the effects of various treatments for RA on the synovium has been studied, and the principal results of these data are presented in table 1.

2.2 Pathogenesis of Synovitis

Synovial tissue inflammation is preceded by activation and proliferation of endothelial cells that form new blood vessels (angiogenesis) as one of the earliest changes. The newly activated vessels are the gateway for leukocyte infiltration into the synovium, actively recruiting immune cells into the tissue. This results in an expanding synovial pannus

characterised, in RA, by hyperplasia of the intimal lining layer and often invasion of pannus cells into the nearby bone producing erosions. Therefore, the synovium is the target tissue in RA and if studies are confined to examining cellular and molecular alterations in the peripheral blood then important information may be completely ignored. For example, Th17 cells are expanded in the blood of some RA patients, this lead to clinical trials of anti-IL17 monoclonal antibodies, however as limited Th17 expansion occurs within the synovium, this therapeutic approach achieved little effect[78]. Indeed, studies have shown enrichment of ex-TH17 cells at the site of inflammation in SF and ST from patients with RA[79]. Additionally, the primary invasive cells in RA are the FLS but these have not yet been associated with a circulating biomarker[80].

2.3 Early Arthritis and Early Diagnosis

Some progress has been made in earlier diagnosis of RA , however signs of joint destruction may already be present at the time of diagnosis.[81] We know today that early, aggressive treatment is more successful than delayed treatment.[82, 83] Therefore the utility of biomarkers in securing a diagnosis as early as possible will allow treatment in the most timely manner, securing the best outcomes.[84] Those with undifferentiated arthritis may benefit most from this. Although ACPA are reasonably specific (96%), the diagnostic sensitivity in early arthritis is 57%.[82] Up to 30% of RA patients never develop ACPA.[85] An association has been defined between the presence of circulating ACPA and subsequent development of RA in subjects with arthralgia,[87] and with bone erosions in early untreated subjects.[88] Delay in diagnosis of RA may arise from either a lack of a definitive biomarker, or a failure to meet current diagnostic criteria, and these criteria have a significant reliance on biomarkers. Therefore, despite the advent of ACPA, there remains a need to identify further and specific susceptibility biomarkers. Recently, biomarkers for RA in those without detectable circulating ACPA have been identified, and this RA subset represent an important group to study, and may contribute greatly to our understanding of the disease pathogenesis.[89, 90]

The so-called ‘at-risk of arthritis’ cohorts have been the subject of much research in recent years. One potential corollary of this is the promise of cure and prevention of RA, where the initial break in self-tolerance is identified and targeted therapeutically.[91]

A positive ACPA status in those with arthralgia is associated with the subsequent development of arthritis in only about 20-30% of these people after 30 months of follow up.[92, 93] The synovial tissue of patients who are at risk of arthritis has also been examined in two relatively small studies Little evidence of synovitis was found in the first and subtle T-cell infiltration was noted in the second.[94] Data on alternative tissues such as lung and lymph node that may be important in the very early stages of arthritis as sites of first antigen presentation.[94, 95]

It is suggested that a 'window of opportunity' may exist during which RA can be most successfully treated. In initial studies few molecular differences had been observed in the synovium comparing early and late disease.[23, 96] Recently, a highly expanded, specific T-cell clone has been identified in early RA, which underlines the importance of T-cells in early stage disease.[97] Epigenetic changes in FLS over time may define the different stages of RA after clinical onset of the disease.

In recent preliminary reports of ultrasound guided biopsies in unselected treatment-naïve, early arthritis patients compared to established RA, there was increased tissue expression of macrophage derived chemokines - CXCL4 and CXCL7 in RA only during the first 3 month window of symptom duration, and not later in disease.[98]

Synovial biopsy may be useful, as a diagnostic and prognostic tool, for the differential diagnosis in early inflammatory arthritis in whom synovial CD22 and CD38 expression may distinguish between RA and non-RA disease.[99] The value of synovial biopsy markers as selected diagnostic and prognostic markers to establish an early diagnosis is clearly still evolving.

A recent study included 50 patients with early arthritis, who had undergone synovial biopsy at inclusion and were followed for two years.[100] The focus was on the angiogenic processes in the initiation and perpetuation of synovial inflammation, in particular vascular endothelial growth factor (VEGF) and angiopoietins 1 and 2 (Ang-1 and Ang-2) and their tyrosine kinase receptors VEGFR and TIE-2. Expression of TIE-2 was significantly increased in the group with erosive disease as compared to the group with a self-limiting disease, and plasma–TIE-2 was significantly increased in the groups with persistent non-erosive disease and persistent erosive disease as compared to the group with self-limiting disease. Similarly, JNK activation is elevated in RA patients compared to undifferentiated arthritis, before classification criteria are met.[101]

Although more research is needed, these studies suggest that a synovial biopsy at disease presentation could be a useful tool for both patients and physicians, for early disease stratification into short self-limiting course versus severe persistent inflammatory course, and in the former between erosive versus non erosive disease, thereby informing the most appropriate treatment strategy.

2.4 'Personalised Medicine' and Disease Stratification

In addition to diagnostic problems, predicting disease course is imprecise. Identification of a subgroup of early arthritis patients who will develop destructive disease may present a significant advance in selecting the most effective treatment for an individual patient.[102, 103] This is the so-called 'tailor-made' treatment, informed by biomarkers, used to assess what

has been referred to as 'disease signatures'.[98] A more accurate description of this process is disease 'stratification'.[104,105]This concept proposes that a disease can be stratified into distinct subsets that exhibit differential outcomes and responses, each subset labelled by a biomarker or combination thereof.

This is important as therapies are commonly selected on a trial and error basis, but less than 50% of RA patients experience a 50% improvement in their arthritis in response to any single biological therapy.[106–108] In the time that an ineffective treatment is administered, the disease may progress and patients may be potentially exposed to unnecessary adverse events. Therefore biomarkers that predict response to a given treatment will be of great clinical utility. Synovial biomarkers are likely to be of the greatest clinical utility and a great deal of work has concentrated on studying features of inflamed synovium in RA patients with samples taken after clinical improvement following treatment. More recently, a number of studies have analysed the predictive capabilities of synovial tissue biomarkers for disease course and response to therapy.

2.5 Recent advances

Synovial tissue biopsy procedures and analysis are more widely available throughout the world.[53] This will inevitably enable a targeted approach to identifying biomarkers in synovial tissue.

With respect to disease stratification, sensitivity and specificity can be theoretically improved by combined use of biomarkers. For example a positive clinical response of RA to anti-tumour necrosis factor treatment with etanercept has been demonstrated using a biomarker signature generated by 13 autoantibodies and 11 cytokines. This study included three ethnically distinct populations, and for North Americans it demonstrated a positive predictive value of 71%, although independent validation is required.[11]

The advent of new proteomic, transcriptomic and genomic technologies, and the ability to combine clinical and radiological markers with these technologies, should make stratifying disease the norm in the future. It is possible that disease stratification will become so sub-categorised such that it is truly approaching personalised medicine. The 'omics' approach has been usefully applied to identify key players and protein interactions in several diseases. Studying the genome, the RNA or the protein will each have different sets of bias and variance, and it has been argued that combined approaches may lead to a more accurate assessment of important protagonists.[104]

Proteomics offers the advantage that the functional units of the cell are being studied directly, likely most accurately representing what is actually happening in the synovium. The development of technologies such as SomaLogics that have the power to measure thousands of proteins in small tissue volumes has the potential to allow a more complete

characterisation of the disease network of RA. In RA the proteomics approach has so far focussed on peripheral blood mononuclear cells, serum and synovial fluid[72,73,109,]; the possibility that the synovial tissue itself may hold the key to unlocking the disease network has yet to be fully exploited. Furthermore, new technologies in protein separation, processing and identification are expected to increase proteome coverage.

In relation to transcriptomic analysis, microarray technology has been, to date, the most frequently employed strategy in the field of biomarker research. This facilitates the identification of candidate genes in pathophysiological processes. However, gene expression levels do not always predict protein levels, due to transcriptional and translational regulatory mechanisms and the activity of protein degradation processes.[17] A good example of the use of transcriptomic data was demonstrated while determining a rule-based classification that allows differentiation between RA and osteoarthritis.[110]

Microarrays contain probes for thousands of different genes that makes them suitable for screening large cohorts. The high throughput techniques used in transcriptomics, however, also allow detection of significant gene expression differences with modestly sized cohorts.[111] Transcriptomic analysis is already being used to examine the gene signature of synovial tissue, augmented by the newer sequencing technologies that permit deeper transcriptional coverage than microarrays, including spliced variants.

There have been a number of studies where DNA array technology used to study gene expression in RA has been shown to be a useful and practical methodology. Different subtypes of RA patient synovia have also been characterised by gene expression analysis.[112,113] Gene-expression variance among RA patients has been described impacting several pathways involved in cell proliferation, cell survival, angiogenesis and regulation of inflammation.[114]

Biomarkers

3.1 General Considerations

3.2 Cellular Composition

Simple cell count densities (or cellular infiltration) were appreciated as synovial tissue biomarkers associated with RA, more than 20 years ago. In a study published in 1989, a group showed that there was a decrease in T cell numbers after at least 6 months of gold treatment. They also reported a reduction in the ratio of T-helper cells to T-

suppressor/cytotoxic cells in those who were treated successfully. Macrophages were not reported in this study. Furthermore, the number of biopsy samples where B cells could be identified decreased from 36% before successful treatment to 7% after treatment.[36]

The most convincing evidence for a cellular biomarker of treatment response points to the use of CD68 macrophages. Patients taking prednisolone had a reduction in synovial macrophages, expressing cell surface CD68, after two weeks of treatment compared with controls. The reduction in CD68 staining cells was mostly attributable to a decrease in the number of macrophages localising to the synovial sublining. There was also a decrease in the CD4 and CD5 (T and B cells) and CD38 (plasma cells) and CD55 (fibroblast-like synoviocyte (FLS)) cells.[42]

In an earlier study a reduction in synovial macrophages was observed 12 weeks after gold therapy. CD68 cells were most commonly identified in all layers independently of the site of synovial biopsy. No significant change in lymphocyte numbers was noted following treatment.[115]

A significant reduction in macrophages in the synovial sublining region following treatment with disease-modifying antirheumatic drugs (DMARDs), mostly methotrexate and gold, was demonstrated in another study.[116] This was particularly pronounced in those who were responding clinically by ACR criteria. Although a significant reduction in memory T cells was observed, (and this was interestingly associated with CRP reduction), memory T-cells could still be found in the synovium of patients who attained remission.

Synovial macrophages were also significantly reduced in the sublining after 16 weeks of treatment with leflunomide, and in the intimal lining layer after 16 weeks of methotrexate monotherapy. Synovial T cell numbers were decreased with both treatments but did not reach statistical significance in this study.[41] Whilein a similar study, after 16 weeks of methotrexate, a decrease in synovial CD3, CD8, CD38, CD68 and Ki67 were demonstrated to be statistically significant. Notably CD4 infiltration was not reduced in this study.[117]

Treatment with infliximab has been shown to reduce CD3 (T cell) in repeat synovial biopsies taken 4 weeks after treatment, and this finding was associated with clinical response.[39] In ten patients with longstanding RA who received infliximab, reduced numbers of synovial CD3 (T cells), CD22 (B cells) and CD68 macrophages, 2 weeks after treatment were demonstrated in a separate study.[45] In a study of infliximab versus placebo in which 24 patients with active RA underwent arthroscopy and biopsy before, and 48 hours after infliximab, revealed a significant reduction in CD68 intimal macrophages, as well as a non-statistically significant reduction in CD68 macrophages, T cells and plasma cells in the sublining. In a large prospective study in 143 RA patients the clinical response to infliximab was predicted by the number of TNF producing cells, CD68 macrophage subsets and synovial expression of TNF.[118] In a follow-up study, the number of lymphocyte aggregates was also predictive of the clinical response.[119] Positivity for lymphocyte aggregates

increased the power to predict the clinical response, when analyzed in a prediction model that included baseline disease activity evaluated by the Disease Activity Score in 28 joints, ACPA positivity, and synovial TNF expression.

Anakinra, a specific Il-1 antagonist, has also been shown to significantly reduce the synovial intimal macrophage population.[43] A significant decrease of intimal lining CD68 macrophages was observed following rituximab infusion in responders.[54]

Synovial response to rituximab has also been assessed by serial biopsy. A series of 6 patients with seropositive RA who had synovial biopsy before treatment with rituximab, and then 4 were re-biopsied after 8 weeks has been reported. The authors assert that although it is known that rituximab depletes circulating B cells, as well as B cells in salivary glands, little is known of its effect on synovial tissue. 4/6 agreed to follow up biopsy. 2 had complete depletion of CD20, 1 had no change and 1 biopsy was insufficient to analyse.[120]

In other studies rituximab induced a similar variable depletion in synovial B cells with an indirect decrease in macrophages, T cells and plasma cells at the time of the clinical response.[121,122] Of interest, the change in plasma cells was associated with the clinical response.

The utility of CD68+ macrophages in the sublining layer as a candidate biomarker was systematically tested across different interventions and kinetics.[123] It was shown that changes in numbers of synovial sublining CD68+ macrophages correlate with clinical improvement independently of the therapeutic strategy. A study designed to determine if the correlation between the change in number of synovial sublining CD68 cells and change in DAS28 was confirmed in a multicentre study with excellent inter-centre agreement.[124] The number of CD68 macrophages decreases with a reduction in disease activity as measured by the DAS, thus demonstrating that CD68 numbers could be used as a biomarker of therapeutic response.[123]

Furthermore, synovial CD68 expression is superior to clinical evaluation as it is less susceptible to both the placebo effect and expectation bias (59% of delegates at OMERACT agreed)[123, 125]. It could therefore be used to assess the therapeutic efficacy of novel treatments.[124] In conclusion, synovial macrophage CD68 expression as a synovial biomarker demonstrates validity, reliability and feasibility is as a biomarker of disease activity and response to treatment both in early and established RA.

A number of studies addressed whether markers of synovitis are associated with clinical phenotype or development of a persistent, erosive disease course. In two large studies in established RA, large lymphocyte aggregates were found in around 30% of patients but did not associate with a clinical phenotype.[126,127] In early arthritis, the presence of lymphocyte aggregates did not predict an aggressive disease course and aggregates were rapidly diminished by several anti-rheumatic treatments.[119,128] Taken together, these studies suggest that lymphocyte aggregates are a pro-inflammatory phenomenon and not a persistent primary driver of synovitis. In contrast, as described above, biomarkers of

angiogenesis, namely the activation of the tyrosine kinase receptor TIE-2, as well as increased JNK expression predicted an aggressive disease course in early arthritis patients.[101]

3.3 Cytokines

The increased expression of several cytokines in the inflamed synovial tissue is well established, and for TNF and IL-6 concentrations correlation with disease activity, independent of disease duration, has been demonstrated.[27] The levels of CCL2/MCP-1 were also found to be increased in RA serum and synovial tissue.[50]

With regards to treatment effect, the expression of IL-1ß and TNF was 40% (95% CI 18–56%) and 52% (95% CI 10–74%) respectively lower following prednisolone therapy compared with placebo. Notably, this effect was mainly attributable to changes in the synovial sublining, and appeared to correlate with clinical improvement.[42] Significant cytokine expression changes after 12 weeks of gold treatment, in three areas of synovium; lining, perivascular and connective tissue, have also been reported. In the intimal lining layer, IL-1α, IL-1ß and IL-6 levels were statistically significantly reduced after treatment, and this seemed to correlate with clinical response. TNF was also reduced in all three areas, but did not reach statistical significance in the lining.

TNF was only slightly reduced in synovial samples after 16 weeks treatment with either methotrexate or leflunomide. IL-1ß was only moderately reduced in the leflunomide-treated patients while reductions in the methotrexate patients were significant, which highlights potential different mechanism of action between DMARDs.[41] In a separate study IL-1ß, but not IL-1α was shown to have a statistically significant reduction in expression after 16 weeks of treatment with methotrexate, and this again seemed to correlate with clinical response.[117]

In biopsy samples of ten active RA patients taken 2 weeks after infliximab, IL-8 and MCP-1 were shown to be reduced in both the lining and sublining, and, despite a downward trend in synovial expression of Gro α, RANTES, and MIP-1b this was not significant.[45]

Acute serum amyloid A (A-SAA) expression and production has been demonstrated in RA synovial tissue and A-SAA induces angiogenesis, cell matrix interactions, chemokine and MMP expression in RA.[130] A–SAA has a significant role in the inflamed joint increasing expression of MMP-1, MMP-3, MMP-13, and MMP/TIMP expression in RA FLS and synovial explants. Furthermore, blockade of its receptor (scavenger receptor class B type 1 (SR-B1)) and TLR2 inhibited migration and invasive mechanisms. Importantly, A-SAA has the ability to induce TNF expression in RA synovial explant cultures, while baseline serum A-SAA levels correlated with the 28-joint swollen joint count and 1-year radiographic progression

independently. Therefore, A-SAA is a promising biomarker of disease activity both in the synovium and in the serum.[131]

3.4 Chemokines

Leucocytes are attracted to the target tissue by soluble chemotactic cytokines termed chemokines, released from activated cells in the tissue to stimulate leucocyte migration through the endothelial barrier.[132] The chemokines IL8/CXCL8 and MCP-1/CCL2, among others, are expressed abundantly in RA synovial tissue. Previous work has shown that the development of clinical signs of RA synovial inflammation is specifically associated with increased synthesis of the CXCL8[133] and expression in synovial tissue reflects response to therapy in RA patients. In addition, a proof of concept study of an oral CCR1 antagonist in RA patients showed significant reduction in synovial macrophages and chemokine expression.[134]

3.5 Growth Factors/Adhesion Molecules

ICAM-1 expression was significantly reduced in patients treated with both leflunomide and methotrexate. Notably, a decrease in ICAM-1 was seen in those that responded to leflunomide and to methotrexate, while non-responders did not experience a statistically significant decrease. VCAM-1 was reduced in both groups, but this difference was significant only in the leflunomide-treated patients.[41]

Another study demonstrated that VCAM-1 and E-selectin were both statistically significantly reduced in expression after 16 weeks of treatment with methotrexate, but in this study ICAM-1 did not reach statistical significance.[117] Treatment with infliximab has been shown to reduce VCAM-1 and E-selectin in repeat biopsies taken 4 weeks after treatment.[39]

In relation to treatment with anakinra, a patient taking the dose of 150mg/day, was shown to have a 74% reduction in synovial membrane E-selectin, but the 5 patients taking the lower dose (30mg/day) did not demonstrate this. No change was seen in P-selectin. A significant decrease in ICAM-1 and VCAM-1 was seen in the high dose patients, and a small decrease in 2 of the 5 on the lower dose of anakinara.[43]

3.5 Mediators and Products of Bone, Cartilage and Tissue Degradation

Type II collagen is the main collagen of articular cartilage, and is excessively degraded in RA. It is known that collagen biomarker and MMP levels predict radiographic progression of RA,

and therefore may act as a prognostic biomarker.[135, 136] A study with the primary objective of attempting to understand more about the mechanism of action of methotrexate (19 subjects) and leflunomide (16 subjects) demonstrated that MMP-1 was significantly reduced by both. The level of TIMP-1 was significantly reduced in the leflunomide-treated patients, but not the methotrexate-treated patients. Furthermore, both drugs reduced the overall expression of MMP-1 and the MMP-1: TIMP-1 ratio after 4 months of treatment. The changes were more pronounced in patients who fulfilled the ACR 20% response criteria.[41]

A number of studies analyzed the effect of immunomodulatory treatment on synovial mediators of bone destruction. Treatment with both infliximab and etanercept increased the expression of osteoprotegerin (OPG) in synovial tissue and had no effect on RANKL, resulting in an increased OPG:RANKL ratio.[49] In contrast, rituximab induced a 99% decrease in receptor activator of nuclear factor κB (RANK)-positive osteoclast precursors and a decrease of 37% in RANKL and a trend towards reduced synovial OPG expression. In serum, both OPG and RANKL levels were significantly reduced, but the OPG/RANKL ratio increased (157%).[137] Finally, abatacept did not exert a significant effect on synovial OPG, RANK or RANKL mRNA expression in a study in 16 patients.[138]

The family of S100 proteins are a closely related group of low-molecular weight (9–14 kDa) acidic calcium-binding proteins. Originally described in oesophageal epithelium, as well as neutrophils and macrophages, they are involved in calcium dependent cell activities such as cytoskeleton regulation and cell migration and adhesion. The extracellular role of these proteins is of interest as they have been found to be overexpressed in inflammatory compartments. They are in effect pro-inflammatory cytokines. S100A12 has important activities in relation to innate and acquired immune responses.[139] One study using quantitative proteomics demonstrated an association between the severity of joint erosion in RA and the S100 proteins A8, A9 and A12 levels.[109] The S100 proteins myeloid-related protein (MRP)-8 and MRP-14 regulate myeloid cell function and control inflammation. Before initiation of treatment, responders to targeted treatments showed significantly higher MRP8/14 protein complex levels compared with non-responders. Moreover, in responders to adalimumab, infliximab or rituximab treatment, MRP8/14 levels decreased after 4 weeks of treatment, but not non-responders.[140]

3.6 Antigens and Antibodies

Expression of antigenic proteins has been described in RA synovial tissue. The presence of deiminated proteins, such as the α- and β-chains of fibrin, in RA synovium appeared to be major antigenic targets of ACPAs.[141] In addition, anti-Sa antibodies that recognize deiminated vimentin appear to be specific for RA and have been isolated from RA synovium.[142] Finally, intracellular citrullinated proteins colocalizing with ACPA reactivity have been demonstrated in RA synovium.[143] but the presence of citrullinated antigens is not

specific for RA synovial tissue.[144] It has also been shown that anti-fillagrin antibodies are produced by local plasma cells resident in the RA pannus.[145]

3.7 Genes and Transcripts

In a study in 18 RA patients treated with infliximab several biological processes, related to inflammation, were up-regulated in pre-treatment synovial tissue biopsies in patients who responded to therapy.[146] In a larger follow-up study, Lindberg *et al* reported the results of RNA analysis of synovial biopsies of 62 patients with RA before treatment with infliximab. They found that the presence of lymphocyte aggregates dominated the expression profiles and that there was a significant overrepresentation of lymphocyte aggregates in patients who had a good response, which confounded the analysis. Nonetheless, in those that were lymphocyte aggregate positive, 38 transcripts were associated with differences between good and non-responders.[147]

In a study of paired synovial biopsies of RA patients, before and 12 weeks after adalimumab, genes were differentially expressed between biopsies of responders and non-responders. These genes could be split into two distinct families: genes involved in the regulation of immune responses and genes involved in the regulation of cell division. To confirm the microarray findings, synovial expression of selected molecules was assessed using specific antibodies. Synovial expression of IL-7R, CXCL11, IL-18, IL-18rap, and MKI67 was significantly higher in poor as compared with moderate and good responders, thereby serving as a potential biomarker of response to adalimumab.[148]

In another study of paired synovial biopsies of RA patients before and after rituximab treatment clinical responders demonstrated higher expression of macrophage and T cell genes, while clinical poor responders showed higher expression of interferon-α and remodelling genes.[149]

3.8 Other

The properties of the cells in the inflamed synovium differ markedly from normal cells Profound hypoxia in the inflamed synovial membrane has been described *in vivo*.[30] Low tissue partial oxygen pressure (tPO2) levels in the inflamed synovial joint tissue are significantly associated with increased markers of macroscopic and microscopic inflammation. There is an association of tPO2 with macroscopic synovitis as well as CD68 and CD3 cell infiltrate in the sublining, and various pro-inflammatory cytokines (TNFα, IL1β, IFNγ and the chemokine MIP3α). When primary synovial fluid cells were exposed *in vitro* to pO2 levels, similar to those in the inflamed joint, there was a significant increase in cell migration.[150]

Conclusion and Current Limitations

Much of the work on serial synovial biopsies has been performed on patients with known diagnoses, and has been performed to investigate responses to treatment. There remains a critical need for identifying biomarkers for diagnosis which can be applied in clinical practice.

Biomarkers may reduce the time taken and the number of patients required to screen for the potential efficacy of new drugs.[52,151] The number of patients with active disease eligible to participate in studies is limited. As with all trials, the number of patients who are to be put at risk by exposure to drugs at an early stage of development, as well as to be placed on placebo, are restricted by ethical considerations.[152]

Although finding biomarkers in peripheral blood is attractive because it is more feasible and less invasive than synovial biopsy, since inflamed synovium is the ultimate target of inflammation, it should be a potentially rich source of potential biomarkers. Furthermore, many confounding factors might interfere with peripheral blood profiles. Some authorities have suggested that a more targeted approach to searching for serum markers should be to first identify potential biomarkers in the inflamed synovial joint, and later studying the plasma for the presence of the same biomarker.[140] Such an approach in RA patients has demonstrated clinical utility when candidate peripheral biomarkers of synovial pathotype predicted response to biologic therapy.[153]

Although new technology has enabled faster and more complete analyses of proteins, because of the high complexity in protein and protein isoforms in the synovial joint, interpreting the results of 'shotgun' proteomics is a challenging endeavour.

New technologies are experiencing difficulties. Expression levels from three widely used microarray platforms demonstrated poor reproducibility.[154] In addition, as there are high levels of background signals in array datasets, there is a decreased sensitivity to transcripts present in low numbers.[155]

The development of high quality immunoanalytical assays can be slow and expensive. This makes the verification of candidate biomarkers a challenging process, and at the moment, despite the increase in availability of means to biopsy synovial tissue, there remains a lack of diagnostic makers.

While there are a great many genomic biomarkers that can predict response to treatment, or those at most risk of adverse events in many areas of medicine, rheumatology appears to have experienced only limited benefit from this emerging field. Many studies have attempted to identify biomarkers to predict response to anti-TNF treatment, but to our knowledge, only those reported above have used synovial tissue to search for these.[119,147,148]

In addition, where data from control synovial tissue specimens is available, osteoarthritis is often used as a disease control, although it is increasingly recognised that osteoarthritis has an underlying inflammatory response, albeit significantly limited and less associated with specific autoimmunity than RA.

It is likely that in the near future a reasonable goal will be to stratify disease before the phenotype is established, and this represents an early step toward eventual 'personalised medicine'. Identifying surrogate markers is therefore an aim for which synovial tissue is an indispensable research tool.

	Cells	Molecular marker	Implications	References
Pathogenesis of disease	Fibroblast-like synoviocytes	DNA methylation	Jak-STAT pathway *HOX* genes	Ai, R., et al. Nat Commun. 10, 11
	Macrophages	CD68 surface antigen	Central effector cell	Tak PP, Bresnihan B. Arthritis Rh
	T cells	CD3 / CD45Ro / Th17	Pivotal immune cells	Kobezda, T., et al. Nat Rev Rheum
	B cells	CD20 / CD22	Production of antibodies; T-cell cooperation	Humby, F., et al. PLoS Med 6, e1
Changes upon targeted therapy	Macrophage	CD68	Correlates with change in disease activity	Dolhain, R. J., et al. Rheumatol 3
	T cells	CCR7		Smith, M. D., et al. Rheumatol 40
	B cells	CD20 / CD22		Walsh, C. A. E., et al. Clin. Exp. Rh
Candidate synovial tissue biomarkers including proteins and genes		ASAA MRP8/14 ICAM-1 MMP-1/-3 CCR1 OPG/RANKL TIE-2	Many are measurable in the synovium and in the circulation	Mullan, R.H., et al. Arthritis Rheu Choi, I.Y., et al. Ann Rheum Dis 7 Kraan, M. C., et al. Arthritis Rheu Catrina, A.I., et al. Arthritis Rheu Haringman, J.J., et al. Ann Rheum Catrina, A.I., et al. Rheumatol 41 Boumans, M.J., et al. Ann Rheum

		JNK		de Launay, D., et al. Ann Rheum
Synovial markers of remission		CD68		Smith, M. D., et al. Rheumatol 40

References

1. Tak, P.P., Bresnihan, B. The pathogenesis and prevention of joint damage in rheumatoid arthritis: advances from synovial biopsy and tissue analysis. *Arthritis Rheum.* **43**, 2619-2633 (2000)

2. Mitchell, D. M., *et al.* Survival, prognosis, and causes of death in rheumatoid arthritis. *Arthritis Rheum.* **29,** 706–714 (1986).

3. Pincus, T., *et al.* Severe functional declines, work disability, and increased mortality in

seventy-five rheumatoid arthritis patients studied over nine years. *Arthritis Rheum.* **27,** 864–872 (1984).

4. Wolfe, F., Michaud, K., Gefeller, O., Choi, H. K. Predicting mortality in patients with rheumatoid arthritis. *Arthritis Rheum.* **48,** 1530–1542 (2003).

5. Sokka, T., *et al.* Remission and rheumatoid arthritis: Data on patients receiving usual care in twenty-four countries. *Arthritis Rheum.* **58,** 2642–2651 (2008).

6. Balogh, E., *et al.* Comparison of remission criteria in a tumour necrosis factor inhibitor treated rheumatoid arthritis longitudinal cohort: patient global health is a confounder. *Arthritis Res Ther.* **15,** R221 (2013).

7. Fearon, U., Veale, D. J. Key Challenges in Rheumatic and Musculoskeletal Disease Translational Research. *EBioMedicine.* **1,** 95–96 (2014).

8. Rantapaa-Dahlqvist, S., *et al.* Antibodies against cyclic citrullinated peptide and IgA rheumatoid factor predict the development of rheumatoid arthritis. *Arthritis Rheum.* **48,** 2741–2749 (2003).

9. Hensvold, A. H., *et al.* How well do ACPA discriminate and predict RA in the general population: a study based on 12 590 population-representative Swedish twins. *Ann Rheum Dis.* **76**, 119-125 (2017).

10. Choi, I.Y., *et al.* MRP8/14 serum levels as a strong predictor of response to biological treatments in patients with rheumatoid arthritis. Ann Rheum Dis. **74**, 499-505 (2015).

11. Hueber, W., *et al.* Blood autoantibody and cytokine profiles predict response to anti-tumor necrosis factor therapy in rheumatoid arthritis. *Arthritis Res Ther.* **11,** R76 (2009).

12. Smith, M. D., *et al.* Microarchitecture and protective mechanisms in synovial tissue from clinically and arthroscopically normal knee joints. *Ann Rheum Dis.* **62,** 303–307 (2003).

13. Rhee, D. K., *et al.* The secreted glycoprotein lubricin protects cartilage surfaces and inhibits synovial cell overgrowth. *J Clin Invest.* **115,** 622–631 (2005).

14. Hyc, A., Osiecka-Iwan, A., Niderla-Bielinska, J., Jankowska-Steifer, E., Moskalewski, S. Pro-and anti-inflammatory cytokines increase hyaluronan production by rat synovial membrane in vitro. *Int J Mol Med.* **24,** 579-585 (2009).

15. Blewis, M. E., *et al.* Interactive cytokine regulation of synoviocyte lubricant secretion. *Tissue Eng. Part A* **16,** 1329–1337 (2009).

16. McInnes, I. B., Schett, G. Cytokines in the pathogenesis of rheumatoid arthritis. *Nat Rev Immunol.* **7,** 429–442 (2007).

17. Tchetverikov, I., *et al.* MMP protein and activity levels in synovial fluid from patients with joint injury, inflammatory arthritis, and osteoarthritis. *Ann Rheum Dis.* **64,** 694–698 (2005).

18. Ishiguro, N., *et al.* Relationships of matrix metalloproteinases and their inhibitors to cartilage proteoglycan and collagen turnover and inflammation as revealed by analyses of synovial fluids from patients with rheumatoid arthritis. *Arthritis Rheum.* **44,** 2503–2511 (2001).

19. Chandran, V. Soluble biomarkers may differentiate psoriasis from psoriatic arthritis. *J Rheumatol.* **89,** 65–66 (2012).

20. Billinghurst, R. C., *et al.* Enhanced cleavage of type II collagen by collagenases in osteoarthritic articular cartilage. *J Clin Invest.* **99,** 1534–1545 (1997).

21. Shingleton, W. D., Hodges, D. J., Brick, P., Cawston, T. E. Collagenase: a key enzyme in collagen turnover. *Biochem Cell Biol.* **74,** 759–775 (1996).

22. Lohmander, L. S., Atley, L. M., Pietka, T. A., Eyre, D. R. The release of crosslinked peptides from type II collagen into human synovial fluid is increased soon after joint injury and in osteoarthritis. *Arthritis Rheum.* **48,** 3130–3139 (2003).

23. Tak, P. P., *et al.* Analysis of the synovial cell infiltrate in early rheumatoid synovial tissue in relation to local disease activity. *Arthritis Rheum.* **40,** 217–225 (1997).

24. Humby, F., *et al.* Ectopic lymphoid structures support ongoing production of class-switched autoantibodies in rheumatoid synovium. *PLoS Med.* **6,** e1 (2009).

25. Vossenaar, E.R., et al. The presence of citrullinated proteins is not specific for rheumatoid synovial tissue. *Arthritis Rheum*. **50**, 3485-3494 (2004)

26. Reece, R. J., Canete, J. D., Parsons, W. J., Emery, P., Veale, D. J. Distinct vascular patterns of early synovitis in psoriatic, reactive, and rheumatoid arthritis. *Arthritis Rheum.* **42,** 1481–1484 (1999).

27. Kennedy, A., *et al.* Angiogenesis and blood vessel stability in inflammatory arthritis. *Arthritis Rheum.* **62,** 711–721 (2010).

28. Mullan, R. H., *et al.* Early changes in serum type II collagen biomarkers predict radiographic progression at one year in inflammatory arthritis patients after biologic therapy. *Arthritis Rheum.* **56,** 2919–2928 (2007).

29. Månsson, B., *et al.* Cartilage and bone metabolism in rheumatoid arthritis. Differences between rapid and slow progression of disease identified by serum markers of cartilage metabolism. *J Clin Invest.* **95,** 1071-1077 (1995).

30. Biniecka, M., *et al.* Oxidative damage in synovial tissue is associated with in vivo hypoxic status in the arthritic joint. *Ann Rheum Dis.* **69,** 1172–1178 (2010).

31. Levick, J. R. Permeability of rheumatoid and normal human synovium to specific plasma proteins. *Arthritis Rheum.* **24,** 1550–1560 (1981).

32. Dahl, L. B., Dahl, I. M., Engström-Laurent, A., Granath, K. Concentration and molecular weight of sodium hyaluronate in synovial fluid from patients with rheumatoid arthritis and other arthropathies. *Ann Rheum Dis.* **44,** 817–822 (1985).

33. Decker, B., McKenzie, B. F., McGuckin, W. F., Slocumb, C. H. Comparative distribution of proteins and glycoproteins of serum and synovial fluid. *Arthritis Rheum.* **2,** 162–177 (1959).

34. Swann, D. A., *et al.* Role of hyaluronic acid in joint lubrication. *Ann Rheum Dis.* **33,** 318-326 (1974).

35. Hui, A. Y., McCarty, W. J., Masuda, K., Firestein, G. S., Sah, R. L. A systems biology approach to synovial joint lubrication in health, injury, and disease. *Wiley Interdiscip Rev Syst Biol Med.* **4,** 15–37 (2012).

36. Rooney, M., Whelan, A., Feighery, C. & Bresnihan, B. Changes in lymphocyte infiltration of the synovial membrane and the clinical course of rheumatoid arthritis. *Arthritis Rheum.* **32,** 361–369 (1989).

37. Firestein, G. S., Paine, M. M., Boyle, D. L. Mechanisms of methotrexate action in rheumatoid arthritis. *Arthritis Rheum.* **37,** 193–200 (1994).

38. Tak, P. P., *et al.* Reduction of synovial inflammation after anti-CD4 monoclonal antibody treatment in early rheumatoid arthritis. *Arthritis Rheum.* **38,** 1457–1465 (1995).

39. Tak, P. P., *et al.* Decrease in cellularity and expression of adhesion molecules by anti–tumor necrosis factor α monoclonal antibody treatment in patients with rheumatoid arthritis. *Arthritis Rheum.* **39,** 1077–1081 (1996).

40. Youssef, P. P., *et al.* Variability in cytokine and cell adhesion molecule staining in arthroscopic synovial biopsies: quantification using color video image analysis. *J Rheumatol.* **24,** 2291–2298 (1997).

41. Kraan, M. C., *et al.* Modulation of inflammation and metalloproteinase expression in synovial tissue by leflunomide and methotrexate in patients with active rheumatoid arthritis: Findings in a prospective, randomized, double-blind, parallel-design clinical trial in thirty-nine. *Arthritis Rheum.* **43,** 1820–1830 (2000).

42. Gerlag, D. M., et al. Effects of oral prednisolone on biomarkers in synovial tissue and clinical improvement in rheumatoid arthritis. *Arthritis Rheum.* **50**, 3783–3791 (2004).

43. Cunnane, G., Madigan, A., Murphy, E., FitzGerald, O., Bresnihan, B. The effects of treatment with interleukin-1 receptor antagonist on the inflamed synovial membrane in rheumatoid arthritis. *Rheumatology.* **40,** 62–69 (2001).

44. Catrina, A. I., *et al.* Anti-tumour necrosis factor (TNF)-α therapy (etanercept) down-regulates serum matrix metalloproteinase (MMP)-3 and MMP-1 in rheumatoid arthritis. *Rheumatology*. **41,** 484–489 (2002).

45. Smeets, T. J. M., Kraan, M. C., van Loon, M. E., Tak, P. Tumor necrosis factor α blockade reduces the synovial cell infiltrate early after initiation of treatment, but apparently not by induction of apoptosis in synovial tissue. *Arthritis Rheum.* **48,** 2155–2162 (2003).

46. Kraan, M. C., *et al.* Differential effects of leflunomide and methotrexate on cytokine production in rheumatoid arthritis. *Ann Rheum Dis.* **63,** 1056–1061 (2004).

47. Rooney, T., *et al.* Synovial tissue interleukin-18 expression and the response to treatment in patients with inflammatory arthritis. *Ann Rheum Dis.* **63,** 1393–1398 (2004).

48. van Holten, J., *et al.* A multicentre, randomised, double blind, placebo controlled phase II study of subcutaneous interferon beta-1a in the treatment of patients with active rheumatoid arthritis. *Ann Rheum Dis.* **64,** 64–69 (2005).

49. Catrina, A. I., *et al.* Anti–tumor necrosis factor therapy increases synovial osteoprotegerin expression in rheumatoid arthritis. *Arthritis Rheum.* **54,** 76–81 (2006).

50. Haringman, J. J., *et al.* A randomized controlled trial with an anti-CCL2 (anti-monocyte chemotactic protein 1) monoclonal antibody in patients with rheumatoid arthritis. *Arthritis Rheum.* **54,** 2387–2392 (2006).

51. Makrygiannakis, D., *et al.* Intraarticular corticosteroids decrease synovial RANKL expression in inflammatory arthritis. *Arthritis Rheum.* **54,** 1463–1472 (2006).

52. Gerlag, D. M., Tak, P. P. Novel approaches for the treatment of rheumatoid arthritis: lessons from the evaluation of synovial biomarkers in clinical trials. *Best Pract Res Clin Rheumatol.* **22,** 311–323 (2008).

53. Harty, L. C., Gerlag, D. M., Pitzalis, C., Veale, D. J., Tak, P. P. Synovial tissue analysis for the discovery of diagnostic and prognostic biomarkers in patients with early arthritis. *J Rheumatol.* **38,** 2068–2072 (2011).

54. Thurlings, R.M., et al. Synovial tissue response to rituximab: mechanism of action and identification of biomarkers of response. *Ann Rheum Dis*. **67**, 917-925 (2008)

55. Vergunst, C.E., et al. Modulation of CCR2 in rheumatoid arthritis: a double-blind, randomized, placebo-controlled clinical trial. *Arthritis Rheum*. **58**, 1931-1939 (2008).

56. van Kuijk, A.W., et al. CCR5 blockade in rheumatoid arthritis: a randomised, double-blind, placebo-controlled clinical trial. *Arthritis Rheum*. **54**, 2387-2392 (2006).

57. Vergunst, C.E., et al. Blocking the receptor for C5a in patients with rheumatoid arthritis does not reduce synovial inflammation. *Rheumatology.* **46**, 1773-1778 (2007).

58. Boumans, M.J., et al. Safety, tolerability, pharmacokinetics, pharmacodynamics andefficacy of the monoclonal antibody ASK8007 blocking osteopontin in patients with rheumatoid arthritis: a randomised, placebo controlled, proof-of-concept study. *Ann Rheum Dis*. **71**, 180-185 (2012).

59. Gerlag, D. Tak, P. P. How to perform and analyse synovial biopsies. *Best Pract Res Clin Rheumatol.* **23,** 221–232 (2009).

60. Kane, D., Veale, D. J., FitzGerald, O. & Reece, R. Survey of arthroscopy performed by

rheumatologists. *Rheumatology* **41,** 210–215 (2002).

61. Lazarou, I. *et al.* Ultrasound-guided synovial biopsy: a systematic review according to the OMERACT filter and recommendations for minimal reporting standards in clinical studies. *Rheumatology.* **54**, 1867-1875 (2015)

62. Kraan, M. C., *et al.* Comparison of synovial tissues from the knee joints and the small joints of rheumatoid arthritis patients: Implications for pathogenesis and evaluation of treatment. *Arthritis Rheum.* **46,** 2034–2038 (2002).

63. Soden, M., *et al.* Immunohistological features in the synovium obtained from clinically uninvolved knee joints of patients with rheumatoid arthritis. *Br J Rheumatol.* **28,** 287–292 (1989).

64. Kraan, M. C., *et al.* Asymptomatic synovitis precedes clinically manifest arthritis. *Arthritis Rheum.* **41,** 1481–1488 (1998).

65. Ai, R., et al. Joint-specific DNA methylation and transcriptome signatures in rheumatoid arthritis identify distinct pathogenic processes. *Nat. Commun.* 7:11849 doi: 10.1038/ncomms11849 (2016).

66. Frank-Bertoncelj, M., et al. Epigenetically-driven anatomical diversity of synovial fibroblasts guides joint-specific fibroblast functions. *Nat. Commun.* **23**:14852. doi: 10.1038/ncomms14852 (2017)

67. Kirkham, B., *et al.* Intraarticular variability of synovial membrane histology, immunohistology, and cytokine mRNA expression in patients with rheumatoid arthritis. *J Rheumatol.* **26,** 777–784 (1999).

68. Smeets, T. J. M. *et al.* Analysis of the cell infiltrate and expression of matrix metalloproteinases and granzyme B in paired synovial biopsy specimens from the cartilage-pannus junction in patients with RA. *Ann Rheum Dis.* **60,** 561–565 (2001).

69. Youssef, P. P., *et al.* Quantitative microscopic analysis of inflammation in rheumatoid arthritis synovial membrane samples selected at arthroscopy compared with samples obtained blindly by needle biopsy. *Arthritis Rheum.* **41,** 663–669 (1998).

70. Smith, M. D., *et al.* Standardisation of synovial tissue infiltrate analysis: how far have we come? How much further do we need to go? *Ann Rheum Dis.* **65,** 93–100 (2006).

71. Bresnihan, B., Tak, P. P., Emery, P., Klareskog, L., Breedveld, F. Synovial biopsy in arthritis research: five years of concerted European collaboration. *Ann Rheum Dis.* **59,** 506–511 (2000).

72. Mateos, J., *et al.* Differential protein profiling of synovial fluid from rheumatoid arthritis and osteoarthritis patients using LC–MALDI TOF/TOF. *J Proteomics.* **75,** 2869–2878 (2012).

73. Biswas, S., *et al.* Identification of Novel Autoantigen in the Synovial Fluid of Rheumatoid Arthritis Patients Using an Immunoproteomics Approach. *PLoS One.* **8,** e56246 (2013).

74. de Hair, M.J., . *et al.* Synovial tissue analysis for the discovery of diagnostic and prognostic biomarkers in patients with early arthritis. *J Rheumatol.* **38,** 2068–2072 (2011).

75. Kraan, M. C. *et al.* Alefacept treatment in psoriatic arthritis: reduction of the effector T cell population in peripheral blood and synovial tissue is associated with improvement of clinical signs of arthritis. *Arthritis Rheum.* **46,** 2776–2784 (2002).

76. Canete, J. D., *et al.* Distinct synovial immunopathology in Behcet disease and psoriatic arthritis. *Arthritis Res Ther.* **11,** R17 (2009).

77. van Kuijk, A. W., Tak, P. P. Synovitis in psoriatic arthritis: immunohistochemistry, comparisons with rheumatoid arthritis, and effects of therapy. *Curr Rheumatol Rep.* **13,** 353–359 (2011).

78. Kobezda, T., Ghassemi-Nejad, S., Mikecz, K., Glant, T.T., Szekanecz, Z. Of mice and men: how animal models advance our understanding of T-cell function in RA. *Nat Rev Rheumatol.* **10**, 160-170 (2014) doi: 10.1038/nrrheum.2013.205.

79. Basdeo, S.A., et al. Ex-Th17 (Nonclassical Th1) Cells Are Functionally Distinct from Classical Th1 and Th17 Cells and Are Not Constrained by Regulatory T Cells. *J Immunol*. **198**, 2249-2259 (2017). doi: 10.4049/jimmunol.1600737.

80. Firestein, G.S., McInnes, I.B. Immunopathogenesis of Rheumatoid Arthritis. *Immunity*. 46, 183-196 (2017). doi: 10.1016/j.immuni.2017.02.006

81. van der Heijde, D. M. Joint erosions and patients with early rheumatoid arthritis. *Br J Rheumatol.* **34 Suppl 2,** 74–78 (1995).

82. Lard, L. R., *et al.* Early versus delayed treatment in patients with recent-onset rheumatoid arthritis: comparison of two cohorts who received different treatment strategies. *Am J Med.* **111,** 446–451 (2001).

83. van der Heijde, A., *et al.* The effectiveness of early treatment with 'second-line' antirheumatic drugs. A randomized, controlled trial. *Ann Intern Med.* **124,** 699–707 (1996).

84. Finckh, A., Liang, M. H., van Herckenrode, C. M. & de Pablo, P. Long-term impact of early treatment on radiographic progression in rheumatoid arthritis: A meta-analysis. *Arthritis Rheum.* **55,** 864–872 (2006).

85. Whiting, P. F., *et al.* Systematic review: accuracy of anti-citrullinated Peptide antibodies for diagnosing rheumatoid arthritis. *Ann Intern Med.* **152,** 456–466 (2010).

86. Lee, D. M., Schur, P. H. Clinical utility of the anti-CCP assay in patients with rheumatic diseases. *Ann Rheum Dis.* **62,** 870–874 (2003).

87. Bos, W. H., *et al.* Arthritis development in patients with arthralgia is strongly associated with anti-citrullinated protein antibody status: a prospective cohort study. *Ann Rheum Dis.* **69,** 490–494 (2010).

88. Nielen, M. M. J., *et al.* Antibodies to citrullinated human fibrinogen (ACF) have

diagnostic and prognostic value in early arthritis. *Ann Rheum Dis.* **64,** 1199–1204 (2005).

89. Anderson, A. E., *et al.* IL-6-driven STAT signalling in circulating CD4+ lymphocytes is a marker for early anticitrullinated peptide antibody-negative rheumatoid arthritis. *Ann Rheum Dis.* **75,** 466–473 (2016).

90. Hensvold, A. H., *et al.* Serum RANKL levels associate with anti- citrullinated protein antibodies in early untreated rheumatoid arthritis and are modulated following methotrexate. *Arthritis Res Ther.* **17,** 239 (2015). doi: 10.1186/s13075-015-0760-9.

91. Gerlag, D.M., Norris, J.M., Tak, P.P. Towards prevention of autoantibody-positive rheumatoid arthritis: from lifestyle modification to preventive treatment. *Rheumatology*. **55**, 607-614 (2016). doi: 10.1093/rheumatology/kev347.

92. de Hair, M. J., *et al.* Features of the synovium of individuals at risk of developing rheumatoid arthritis: implications for understanding preclinical rheumatoid arthritis. *Arthritis Rheum.* **66,** 513–522 (2014).

93. van de Sande, M. G. *et al.* Different stages of rheumatoid arthritis: features of the synovium in the preclinical phase. *Ann Rheum Dis.* **70,** 772–777 (2011).

94. Reynisdottir, G., *et al.* Signs of immune activation and local inflammation are present in the bronchial tissue of patients with untreated early rheumatoid arthritis. *Ann Rheum Dis.* **75,** 1722–1727 (2016).

95. van Baarsen, L.G., et al. The cellular composition of lymph nodes in the earliest phase of inflammatory arthritis. *Ann Rheum Dis*. **72**, 1420-1424 (2013) doi: 10.1136/annrheumdis-2012-202990.

96. Baeten, D., *et al.* Comparative study of the synovial histology in rheumatoid arthritis, spondyloarthropathy, and osteoarthritis: influence of disease duration and activity. *Ann Rheum Dis.* **59,** 945–953 (2000).

97. Klarenbeek, P. L., *et al.* Inflamed target tissue provides a specific niche for highly expanded T-cell clones in early human autoimmune disease. *Ann Rheum Dis.* **71,** 1088–1093 (2012).

98. Yeo, L., *et al.* Expression of chemokines CXCL4 and CXCL7 by synovial macrophages defines an early stage of rheumatoid arthritis. *Ann Rheum Dis.* **75,** 763–771 (2016).

99. Kraan, M.C., et al. Immunohistological analysis of synovial tissue for differential diagnosis in early arthritis. *Rheumatology*. **38**, 1074-80 (1999).

100. van de Sande, M. G., *et al.* Local synovial engagement of angiogenic TIE-2 is associated with the development of persistent erosive rheumatoid arthritis in patients with early arthritis. *Arthritis Rheum.* **65,** 3073–3083 (2013).

101. de Launay, D., et al. Selective involvement of ERK and JNK mitogen-activated protein kinases in early rheumatoid arthritis (1987 ACR criteria compared to 2010 ACR/EULAR criteria): a prospective study aimed at identification of diagnostic and prognostic

biomarkers as well as therapeutic targets. *Ann Rheum Dis*. **71**, 415-423 (2012). doi: 10.1136/ard.2010.143529.

102. Drossaers-Bakker, K. W., *et al.* Long-term outcome in rheumatoid arthritis: A simple algorithm of baseline parameters can predict radiographic damage, disability, and disease course at 12-year followup. *Arthritis Rheum.* **47,** 383–390 (2002).

103. Scott, D. L. The diagnosis and prognosis of early arthritis: rationale for new prognostic criteria. *Arthritis Rheum.* **46,** 286–290 (2002).

104. Lindstrom, T. M., Robinson, W. H. Biomarkers for rheumatoid arthritis: making it personal. *Scand J Clin Lab Investig.* **70,** 79–84 (2010).

105. Trusheim, M. R., Berndt, E. R., Douglas, F. L. Stratified medicine: strategic and economic implications of combining drugs and clinical biomarkers. *Nat Rev Drug Discov.* **6,** 287–293 (2007).

106. Edwards, J. C., et al. Efficacy of B-cell-targeted therapy with rituximab in patients with rheumatoid arthritis. *N Engl J Med.* **350,** 2572–2581 (2004).

107. Genovese, M. C., *et al.* Abatacept for rheumatoid arthritis refractory to tumor necrosis factor alpha inhibition. *N Engl J Med.* **353,** 1114-1123 (2005).

108. Moreland, L. W., *et al.* Treatment of rheumatoid arthritis with a recombinant human tumor necrosis factor receptor (p75)-Fc fusion protein. *N Engl J Med.* **337,** 141-147 (1997).

109. Liao, H., *et al.* Use of mass spectrometry to identify protein biomarkers of disease severity in the synovial fluid and serum of patients with rheumatoid arthritis. *Arthritis Rheum.* **50,** 3792–3803 (2004).

110. Woetzel, D., *et al.* Identification of rheumatoid arthritis and osteoarthritis patients by transcriptome-based rule set generation. *Arthritis Res Ther.* **16,** R84 (2014).

111. Smith, S. L., Plant, D., Eyre, S., Barton, A. The potential use of expression profiling: implications for predicting treatment response in rheumatoid arthritis. *Ann Rheum Dis.* **72,** 1118–1124 (2013).

112. Häupl, T., Stuhlmüller, B., Grützkau, A., Radbruch, A., Burmester, G. R. Does gene expression analysis inform us in rheumatoid arthritis? *Ann Rheum Dis.* **69,** i37–i42 (2010).

113. van Baarsen, L. G. M., *et al.* Synovial tissue heterogeneity in rheumatoid arthritis in relation to disease activity and biomarkers in peripheral blood. *Arthritis Rheum.* **62,** 1602–1607 (2010).

114. Huber, R., *et al.* Identification of intra-group, inter-individual, and gene-specific variances in mRNA expression profiles in the rheumatoid arthritis synovial membrane. *Arthritis Res Ther.* **10,** R98 (2008).

115. Yanni, G., Nabil, M., Farahat, M. R., Poston, R. N., Panayi, G. S. Intramuscular gold decreases cytokine expression and macrophage numbers in the rheumatoid synovial

membrane. *Ann Rheum Dis.* **53,** 315–322 (1994).

116. Smith, M. D., *et al.* Treatment-induced remission in rheumatoid arthritis patients is characterized by a reduction in macrophage content of synovial biopsies. *Rheumatology.* **40,** 367–374 (2001).

117. Dolhain, R. J., *et al.* Methotrexate reduces inflammatory cell numbers, expression of monokines and of adhesion molecules in synovial tissue of patients with rheumatoid arthritis. *Rheumatology.* **37,** 502–508 (1998).

118. Wijbrandts, C. A., *et al.* The clinical response to infliximab in rheumatoid arthritis is in part dependent on pretreatment tumour necrosis factor alpha expression in the synovium. *Ann Rheum Dis.* **67,** 1139–1144 (2008).

119. Klaasen, R., *et al.* The relationship between synovial lymphocyte aggregates and the clinical response to infliximab in rheumatoid arthritis: a prospective study. *Arthritis Rheum.* **60,** 3217–3224 (2009).

120. Walsh, C. A. E., Fearon, U., FitzGerald, O., Veale, D. J., Bresnihan, B. Decreased CD20 expression in rheumatoid arthritis synovium following 8 weeks of rituximab therapy. *Clin Exp Rheumatol.* **26,** 656 (2008).

121. Vos, K., et al. Early effects of rituximab on the synovial cell infiltrate in patients with rheumatoid arthritis. *Arthritis Rheum*. 56, 772-778(2007).

122. Kavanaugh, A., *et al.* Assessment of rituximab's immunomodulatory synovial effects (ARISE trial). 1: clinical and synovial biomarker results. *Ann Rheum Dis.* **67,** 402–408 (2008).

123. Haringman, J.J., et al. Synovial tissue macrophages: a sensitive biomarker for response to treatment in patients with rheumatoid arthritis. *Ann Rheum Dis*. **64**,834-838 (2005).

124. Bresnihan, B., *et al.* Synovial macrophages as a biomarker of response to therapeutic intervention in rheumatoid arthritis: standardization and consistency across centers. J *Rheumatology*. **36,** 1800–1802 (2009).

125. Wijbrandts, C.A., et al. Absence of changes in the number of synovial sublining macrophages after ineffective treatment for rheumatoid arthritis: Implications for use of synovial sublining macrophages as a biomarker. *Arthritis Rheum.* **56**, 3869-3871 (2007).

126. Thurlings, R. M., *et al.* Synovial lymphoid neogenesis does not define a specific clinical rheumatoid arthritis phenotype. *Arthritis Rheum.* **58,** 1582–1589 (2008).

127. Cantaert, T., *et al.* B lymphocyte autoimmunity in rheumatoid synovitis is independent of ectopic lymphoid neogenesis. *J Immunol.* **181,** 785–794 (2008).

128. van de Sande, M. G., *et al.* Presence of lymphocyte aggregates in the synovium of patients with early arthritis in relationship to diagnosis and outcome: is it a constant feature over time? *Ann Rheum Dis.* **70,** 700–703 (2011).

129. Tak, P.P., et al. Analysis of the synovial cell infiltrate in early rheumatoid synovial tissue in relation to local disease activity. *Arthritis Rheum*. **40**, 217-225 (1997).

130. Mullan, R. H., *et al.* Acute-phase serum amyloid A stimulation of angiogenesis, leukocyte recruitment, and matrix degradation in rheumatoid arthritis through an NF-kappaB-dependent signal transduction pathway. *Arthritis Rheum.* **54,** 105–114 (2006).

131. Connolly, M., Veale, D. J., Fearon, U. Acute serum amyloid A regulates cytoskeletal rearrangement, cell matrix interactions and promotes cell migration in rheumatoid arthritis. *Ann Rheum Dis.* **70,** 1296–1303 (2011).

132. Haringman, J.J., Ludikhuize, J., Tak, P.P. Chemokines in joint disease: the key to inflammation? *Ann Rheum Dis.* **63**, 1186-1194 (2004).

133. Kraan, M.C., et al. The development of clinical signs of rheumatoid synovial inflammation is associated with increased synthesis of the chemokine CXCL8 (interleukin-8). *Arthritis Res*. **3**, 65-71 (2001).

134. Haringman, J.J., Kraan, M.C., Smeets, T.J., Zwinderman, K.H., Tak, P.P. Chemokine blockade and chronic inflammatory disease: proof of concept in patients with rheumatoid arthritis. *Ann Rheum Dis*. 62, 715-721 (2003)

135. Green, M. J., *et al.* Serum MMP-3 and MMP-1 and progression of joint damage in early rheumatoid arthritis. *Rheumatology.* **42,** 83–88 (2003).

136. Mullan, R.H., et al. Early changes in serum type II collagen biomarkers predict radiographic progression at one year in inflammatory arthritis patients after biologic therapy. *Arthritis Rheum*. **56**, 2919-2928 (2007).

137. Boumans, M. J., *et al.* Rituximab abrogates joint destruction in rheumatoid arthritis by inhibiting osteoclastogenesis. *Ann Rheum Dis.* **71,** 108–113 (2012).

138. Buch, M. H., *et al.* Mode of action of abatacept in rheumatoid arthritis patients having failed tumour necrosis factor blockade: a histological, gene expression and dynamic magnetic resonance imaging pilot study. *Ann Rheum Dis.* **68,** 1220–1227 (2009).

139. Meijer, B., Gearry, R. B., Day, A. S. The Role of S100A12 as a Systemic Marker of Inflammation. *Int J Inflam.* 2012;2012:907078. doi: 10.1155/2012/907078.

140. Choi, I.Y., Gerlag, D.M., Holzinger, D., Roth, J., Tak, P.P. From synovial tissue to peripheral blood: myeloid related protein 8/14 is a sensitive biomarker for effective treatment in early drug development in patients with rheumatoid arthritis. PLoS One. **28**, 9:e106253. doi: 10.1371/journal.pone.0106253. eCollection 2014.

141. Masson-Bessiere, C., *et al.* The major synovial targets of the rheumatoid arthritis-specific antifilaggrin autoantibodies are deiminated forms of the alpha- and beta-chains of fibrin. *J Immunol.* **166,** 4177–4184 (2001).

142. Després, N., Boire, G., Lopez-Longo, F. J., Ménard, H. A. The Sa system: a novel antigen-antibody system specific for rheumatoid arthritis. *J. Rheumatol.* **21,** 1027–33 (1994).

143. Baeten, D., *et al.* Specific presence of intracellular citrullinated proteins in rheumatoid arthritis synovium: relevance to antifilaggrin autoantibodies. *Arthritis Rheum.* **44,** 2255–2262 (2001).

144. Vossenaar, E.R., et al. The presence of citrullinated proteins is not specific for rheumatoid synovial tissue. *Arthritis Rheum*. **50**, 3485-3494 (2004).

145. Masson-Bessiere, C., *et al.* In the rheumatoid pannus, anti-filaggrin autoantibodies are produced by local plasma cells and constitute a higher proportion of IgG than in synovial fluid and serum. *Clin Exp Immunol.* **119,** 544–552 (2000).

146. van der Pouw Kraan, T. C., *et al.* Responsiveness to anti-tumour necrosis factor alpha therapy is related to pre-treatment tissue inflammation levels in rheumatoid arthritis patients. *Ann Rheum Dis.* **67,** 563–566 (2008).

147. Lindberg, J., *et al.* The gene expression profile in the synovium as a predictor of the clinical response to infliximab treatment in rheumatoid arthritis. *PLoS One* **5,** e11310 (2010).

148. Badot, V., *et al.* Gene expression profiling in the synovium identifies a predictive signature of absence of response to adalimumab therapy in rheumatoid arthritis. *Arthritis Res Ther.* **11,** R57 (2009).

149. Gutierrez-Roelens, I., et al. Rituximab treatment induces the expression of genes involved in healing processes in the rheumatoid arthritis synovium. *Arthritis Rheum* **63**, 1246-1254 (2011). doi: 10.1002/art.30292.

150. Ng, C. T., *et al.* Synovial tissue hypoxia and inflammation in vivo. *Ann Rheum Dis.* **69,** 1389–1395 (2010).

151. Colburn, W. A. Selecting and validating biologic markers for drug development. *J Clin Pharmacol.* **37,** 355–362 (1997).

152. van de Sande, M. G. H., *et al.* Evaluating antirheumatic treatments using synovial biopsy: a recommendation for standardisation to be used in clinical trials. *Ann Rheum Dis.* **70,** 423–427 (2011).

153. Dennis Jr., G. *et al.* Synovial phenotypes in rheumatoid arthritis correlate with response to biologic therapeutics. *Arthritis Res Ther.* **16,** R90 (2014).

154. Tan, P. K., *et al.* Evaluation of gene expression measurements from commercial microarray platforms. *Nucleic Acids Res.* **31,** 5676–5684 (2003).

155. Wang, Z., Gerstein, M., Snyder, M. RNA-Seq: a revolutionary tool for transcriptomics. *Nat Rev Genet.* **10,** 57–63 (2009).